*Astronomy & Astrophysics* manuscript no.
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# Photometric variability in the old open cluster M 67 *

## II. General survey**

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Received date / Accepted date

**Abstract.** We use differential CCD photometry to search for variability in $BVI$ among 990 stars projected in and around the old open cluster M 67. In a previous paper we reported results for 22 cluster members that are optical counterparts to X-ray sources; this study focuses on the other stars in our observations. A variety of sampling rates were employed, allowing variability on time scales ranging from $\sim 0.3$ hours to $\sim 20$ days to be studied. Among the brightest sources studied, detection of variability as small as $\sigma \approx 10$ mmag is achieved (with $> 3\sigma$ confidence); for the typical star observed, sensitivity to variability at levels $\sigma \approx 20$ mmag is achieved. The study is unbiased for stars with $12.5 < B < 18.5$, $12.5 < V < 18.5$, and $12 < I < 18$ within a radius of about 10 arcmin from the cluster centre. In addition, stars with $10 < BVI < 12.5$ were monitored in a few small regions in the cluster. We present photometry for all 990 sources studied, and report the variability characteristics of those stars found to be variable at a statistically significant level. Among the variables, we highlight several sources that merit future study, including stars located on the cluster binary sequence, stars on the giant branch, blue stragglers, and a newly discovered W UMa system.

**Key words.** Stars: activity – Stars: variables: general – open clusters and associations: individual: M 67

## 1. Introduction

Photometric variability serves as an important means of identifying stars of interest to the study of stellar structure and evolution. Origins of stellar photometric variability include dynamo-generated magnetic activity, stellar pulsation, and tidal effects related to stellar multiplicity.

With the intent of studying the photometric variability of optical counterparts to known X-ray sources scattered throughout the old open cluster M 67, we have obtained sensitive photometry of stars projected in a roughly square region one-third degree on a side centered 5′ north of the cluster centre. The results of these observations for the X-ray sources are described in Paper I of this series (van den Berg et al. (2001b)). Light curves for nearly 1000 other stars were produced in the course of our analyses. In this paper we present the results of an extensive time-series analysis of the 968 stars included in our observations that are not optical counterparts of X-ray sources known to be members of the cluster.

Our basic goal is to identify those stars that exhibit statistically significant photometric variability of any kind. At the old age of M 67 (4 Gyr; Pols et al. (1998)), most single stars rotate too slowly to exhibit strong dynamo-generated activity, and the sensitivity of our photometry is insufficient to detect the extremely low-level ($\sim$ few $\mu$mag) variations that may arise from solar-analog $p$-mode oscillations (Woodward & Hudson (1983)). Thus, photometric variability in our observations may be an indicator of, e.g., binary interaction (eclipses or ellipsoidal variations), spot-modulated stellar rotation, or stellar activity at levels not detectable in existing X-ray surveys. Periodic variability is especially interesting in these contexts, as a periodicity in the light curve may be fundamentally related to a stellar rotation period, a binary orbital period, etc. But even if a periodicity is not apparent in our data, the detection of photometric variability may point the way to objects that merit further study.

Basic photometry has been performed in M 67 by several authors. Montgomery et al. (1993) have presented a deep ($V \sim 20$) colour-magnitude diagram of the central

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* Tables 1 and 3 are only available in electronic form via anonymous ftp to cdsarc.u-strasbg.fr (130.79.125.5) or via http://www.edpsciences.org

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one-half degree of the cluster, and Fan et al. (1996) have presented spectrophotometry of similar depth from 0.4 $\mu$m to about 1 $\mu$m for stars in a $2^{\circ} \times 2^{\circ}$ region centered on the cluster. In addition, time-series analysis has been performed in M 67, most notably by Gilliland et al. (1991), who conducted a very sensitive ($\sim 100\mu$mag), highly temporally sampled ($\sim 1$ min$^{-1}$) study of stars in the core of the cluster, resulting in several detections of W UMa systems and $\delta$ Scuti variables, as well as tentative detections of other stellar oscillations. This study was confined for the most part to the central few arcmin of the cluster.

The present study complements and extends these previous studies by combining a study of variability (sensitive to $\sigma \sim$ 10–20 mmag) with a reasonably deep ($V \sim 18.5$) colour-magnitude diagram for stars covering a large area around the cluster centre. Furthermore, the ongoing CfA spectroscopic survey (e.g. Latham et al. (1992)) has identified numerous spectroscopic binaries in the cluster among stars brighter than about $V \sim 14$; in this study we incorporate the available knowledge of binarity into our analyses where appropriate.

In Sect. 2, we summarise the photometric data and their analyses. We provide photometry for all of the sources included in our observations, as well as cross-identifications of our sources with those of several previous authors. In Sect. 3, we present the basic results of this study, including an identification of stars exhibiting statistically significant photometric variability, and a colour-magnitude diagram of all sources studied. The colour-magnitude diagram we present shows a well-defined main sequence extending to the limit of our photometry, and an evident binary sequence. Many of the stars identified as photometric variables lie either on the binary sequence, in the region of the blue stragglers, and on the giant branch. Still other stars lie on the cluster main sequence and exhibit apparently irregular photometric variations. Photometric variability at the levels to which this study is sensitive ($\sim$ 1–2%) is uncommon in this cluster among stars that are not known to be X-ray sources or binaries (variability having an occurrence rate of only $\sim 3\%$ among the non–X-ray sources and non-binaries observed by us). We discuss the results of select individual sources in greater detail in Sect. 4, and summarise our findings in Sect. 5.

## 2. Data and analysis

In this section we provide a summary of our observations and of the procedures used in their analysis. For complete details of the data and of the analysis procedures, the reader is referred to Paper I.

### 2.1. Observations

Differential $BVI$ photometry of M 67 was performed during five separate epochs with a total time span of two years. The observations were obtained with 1-meter telescopes at three different observing sites, each with a different field of view (ranging from 3$'$.8 to 23$'$ on a side) and under a range of observing conditions. The five observing runs differ considerably in time span and sampling frequency; the shortest run is the most highly sampled, spanning 2 days with individual measurements taken at roughly 5-minute intervals, while the longest run spans nearly 25 days with measurements taken at intervals of several hours. As each observing run had as its primary target a different set of X-ray sources, the five runs differ in depth and range of stellar magnitudes covered. We encourage the reader to consult the map (Fig. 1) and table (Table 1) in Paper I that more fully describe these observation details.

The result is a database of differential photometric measurements for 990 stars in a region roughly 23$'$ on a side, centred approximately 5$'$ north of the cluster centre. The database is complete in this large area for stars with $12.5 < B < 18.5$, $12.5 < V < 18.5$, and $12 < I < 18$. In addition, the database includes stars with $10 < BVI < 12.5$ in a few small regions within this larger area. Some $U$-band photometry was obtained as well, but as only a small number of stars in a few select regions were observed we do not include the analysis of the $U$-band data here.

Due to the differences in depth and areal coverage of the five observing runs, there is relatively little overlap of stars among the five epochs of data. Thus the light curve of a given star typically spans anywhere from 2 to 25 days with the time-sampling depending on the particular epoch contributing data to that star. Furthermore, stars near the bright or faint extremes of the database may not be present in all three filters depending on the stellar colours.

### 2.2. Data reduction and light curve solution

The roughly 1200 data frames produced in the course of the five observing runs were reduced using standard IRAF[1] procedures. All stellar sources with S/N > 10 were identified with the DAOPHOT task and aperture photometry was performed using the APPHOT.PHOT task. For the purpose of cross-identifying stars in our frames with previous work, astrometry was extracted for all stellar sources identified using the STSDAS.GASP package, producing astrometric solutions with formal internal uncertainties of approximately 0$''$.1 in each direction. Astrometric positions are tied to the coordinate system adopted by Montgomery et al. (1993), resulting in an external uncertainty of approximately 0$''$.4 in each direction.

In Table 1 we present the master list of 977 stellar sources included in our observations, sorted in order of increasing right ascension, which we were able to cross-identify with the database of Fan et al. (1996). The primary stellar identification is that of Fan et al. (1996), and cross-identifications with the studies of various other au-

[1] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

TABLE 1.

| # | S ID | $P_\mu$ | G ID | $P_\mu$ | $P_\mu, r$ | $P_r v$ | Z ID | $P_\mu$ | E ID | F ID | M ID |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1087 | | | | | | | | | | | |
| 1120 | | | | | | | | | | | |
| 1320 | | | | | | | | | | | |
| 1377 | 364 | 0.00 | 364 | 0.00 | 0.00 | | 468 | 0.00 | | | 6470 |
| 1395 | | | | | | | | | | | |
| 1405 | | | | | | | | | | | |
| 1406 | | | | | | | | | | | |
| 1462 | | | | | | | | | | | |
| 1469 | | | | | | | | | | | |
| 1489 | | | | | | | | | | | |
| 1500 | | | | | | | | | | | |
| 1536 | | | | | | | | | | | |
| 1613 | | | | | | | | | | | |
| 1678 | | | | | | | | | | | |
| 1691 | | | | | | | | | | | |
| 1733 | | | | | | | | | | | |
| 1749 | | | | | | | | | | | |
| 1758 | 2301 | 0.00 | 2301 | 0.02 | 0.00 | | 483 | 0.16 | | | |
| 1927 | 625 | 0.91 | 625 | 0.80 | 0.69 | | | | | | |
| 1947 | 626 | 0.67 | 626 | 0.42 | 0.43 | | | | | | |
| 1987 | 633 | 0.00 | 633 | 0.03 | 0.01 | | | | | | |
| 2024 | 630 | 0.96 | 630 | 0.91 | 0.82 | | | | | | |
| 2117 | 624 | 0.02 | 624 | 0.02 | 0.02 | | | | 4-196 | | |
| 2147 | | | | | | | | | | | |
| 2189 | | | | | | | | | | | |

**Table 1.** Master list of all 977 stellar sources included in our observations, sorted in order of increasing right ascension, which we were able to cross-identify with the database of Fan et al. (1996). From left to right: identification number (Fan et al. (1996)); Sanders' identification number and proper-motion cluster-membership probability (Sanders (1977)); Girard et al.'s identification number, proper-motion cluster-membership probability $P_\mu$, proper-motion membership probability taking into account the star's position relative to the cluster centre $P_\mu$,r and radial-velocity membership probability $P_{rv}$ (Girard et al. (1989)); Zhao et al. identification number and proper-motion membership probability (Zhao et al. (1993)); Eggen & Sandage (1964) identification number; Fagerholm (1906) identification number; Montgomery et al. (1993) identificaton number. *Note: Only the first 25 stars are shown here to demonstrate the format of the table. The full table is available only in the electronic version of the paper.*

thors are also given. Various cluster membership estimates from those studies are also provided, when available.

In Table 2 we list 13 stars that appear in our frames but that we could not cross-identify in the Fan et al. (1996) database (within a 2.″5 search radius). For these 13 stars we provide stellar positions derived from our data frames, as well as any cross-identifications to other studies.

Given the highly inhomogeneous nature of our data (all stars do not appear on all data frames), differential photometric light curves are derived with the algorithm for differential photometry of an inhomogeneous ensemble described by Honeycutt (1992), as described in Paper I.

The limiting precision of our differential photometry is a function of stellar brightness and can be established from an examination of the scatter present in the light curves of non-variable stars at each magnitude. The limiting photometric precision as a function of stellar magnitude varies among the five observing runs, but generally speaking the precision of the brightest unsaturated stars in our exposures is flat-field limited to 5–10 mmag. This precision level typically holds for stars up to 2–2.5 mag fainter than the brightest sources, and then becomes photon-noise limited and degrades for still fainter stars. The best overall precision was achieved on our Kitt Peak frames (run 1; see Table 1 in Paper I). In Fig. 1 we show the r.m.s. variations in the $BVI$ light curves of stars from this observing run as a function of mean stellar magnitude. The non-variable stars are defined by the lower envelope of points in this figure. The brightest non-variable stars show r.m.s. variations of 0.007, 0.005, and 0.005 mag in $B$, $V$, and $I$, respectively. The precision begins to degrade noticeably at around 14th mag. For the faintest sources, at about 18.5 mag, the precision is $\sim 0.05$ mag. We have applied a zero-point shift to the instrumental magnitudes in each filter to roughly place our stellar magnitudes on an absolute scale; these shifts were determined by comparing our magnitudes to the published values of Montgomery et al. (1993).

In Table 3 we present mean $BVI$ photometry for the 990 stellar sources in our database. As discussed above, uncertainties in the values listed are a function of stellar brightness: formal uncertainties in the brightest sources are 0.01 mag or less, while the faintest sources observed have formal uncertainties of $\sim$ 5%. We note, however, that our photometry has not been strictly calibrated, so that the uncertainty in the absolute photometry listed in Table 3 is more likely no better than a few percent. In Sect. 3 we use these stellar magnitudes to construct colour-magnitude diagrams for identifying objects of interest.

Table 4 shows how our photometric precision varies as a function of $B-V$ and $V-I$ color for stars on the cluster main sequence. Note that, while these values are representative, due to the inhomogeneous nature of our

TABLE 2.

| # | R.A. | Dec. | S ID | $P_\mu$ | G ID | $P_\mu$ | $P_\mu, r$ | $P_r v$ | Z ID | $P_\mu$ | E ID | F ID | M ID |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 08 48 02.76 | +12 04 48.8 | | | | | | | | | | | |
| B | 08 48 09.35 | +12 00 17.9 | | | | | | | | | | | |
| C | 08 48 24.37 | +12 00 49.3 | | | | | | | | | | | |
| D | 08 48 29.05 | +11 57 29.0 | | | | | | | | | | | |
| E | 08 48 30.40 | +11 56 20.4 | | | | | | | | | | | 5554 |
| F | 08 48 31.39 | +12 05 26.8 | | | | | | | | | | | |
| G | 08 48 32.95 | +11 59 48.3 | | | | | | | | | | | |
| H | 08 48 36.19 | +11 57 37.5 | | | | | | | | | 1-224 | | 5678 |
| I | 08 48 39.90 | +12 13 29.4 | | | | | | | | | | | |
| J | 08 48 40.01 | +11 58 27.2 | 2209b | | 2209b | 0.00 | 0.00 | | | | 1-245 | | 5763 |
| K | 08 48 40.02 | +11 59 44.4 | | | | | | | | | | | 5766 |
| L | 08 48 40.49 | +12 07 28.0 | | | | | | | | | | | |
| M | 08 48 43.95 | +12 15 33.7 | | | | | | | | | | | |

**Table 2.** List of 13 stellar sources included in our observations which we were not able to cross-identify with the database of Fan et al. (1996). The stars are listed in order of increasing right ascension. Columns are as for Table 1, but also included are right ascension and declination coordinates (equinox 1950) as determined from our data frames.

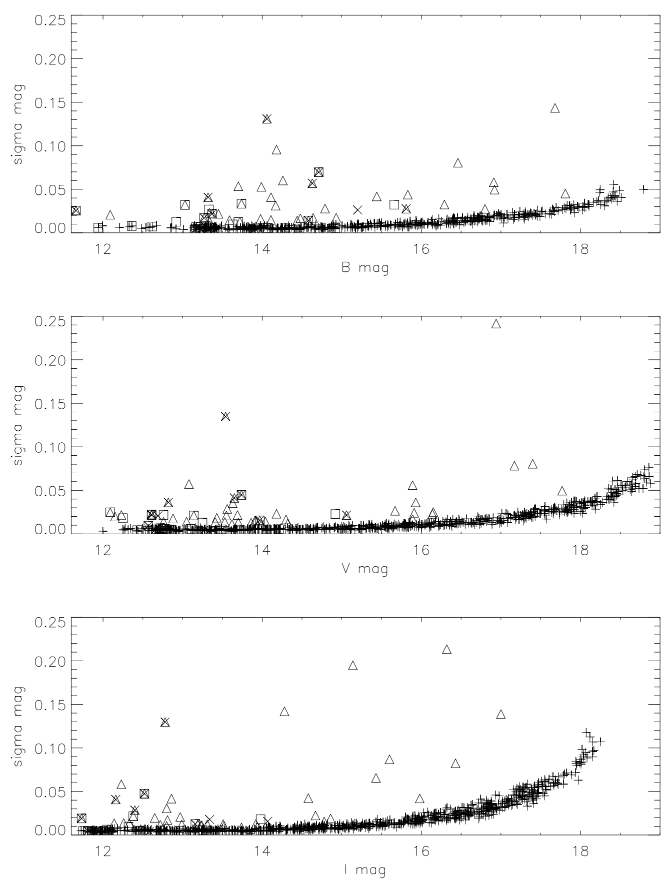



**Fig. 1.** Mean stellar magnitude versus r.m.s. variations in the $B$ (top), $V$ (middle) and $I$ light curves of run 1. Variables are indicated with triangles, spectroscopic binaries with squares, X-ray sources with crosses. Non-variable stars are defined by the lower envelope of points.

TABLE 3.

| # | $B$ | $V$ | $I$ |
|---|---|---|---|
| 1087 | 13.32 | 12.88 | |
| 1120 | 13.68 | 13.17 | |
| 1320 | 15.45 | 14.83 | |
| 1377 | 11.16 | 9.94 | |
| 1395 | 14.32 | 13.73 | |
| 1405 | 15.54 | 14.78 | |
| 1406 | 13.84 | 13.41 | |
| 1462 | 11.81 | 11.14 | |
| 1469 | 14.90 | 14.33 | |
| 1489 | 15.33 | 14.65 | |
| 1500 | 15.21 | 14.35 | |
| 1536 | 14.82 | 14.22 | |
| 1613 | 15.21 | 14.58 | |
| 1678 | 16.00 | 15.27 | |
| 1691 | 15.79 | 15.23 | |
| 1733 | 15.98 | | |
| 1749 | 15.77 | 14.95 | |
| 1758 | 15.39 | 14.62 | |
| 1927 | 15.62 | 14.71 | |
| 1947 | 16.26 | 15.41 | |
| 1987 | 15.02 | 14.47 | |
| 2024 | 14.97 | 14.35 | |
| 2117 | 16.35 | 15.62 | |
| 2147 | 17.27 | | |
| 2189 | | 17.30 | |

[1] These $I$-band measurements were taken through the Gunn $i$ filter.

**Table 3.** Mean $BVI$ photometry for the 990 stellar sources in our database. *Note: Only the first 25 stars are shown to demonstrate the format of the table. The full table is only available in the electronic version of the paper.*

dataset the precision achieved for any particular star may deviate from the values listed in the Table.

### 2.3. Search for variability

To identify photometric variability among the stars in our database, we apply a $\chi^2$ test, as described in Paper I, to compute the probability that each star's light curve is consistent with being constant. As our photometric precision is a function of stellar brightness, our ability to detect low-level photometric variations is necessarily a function

TABLE 4.

| $B-V$ | $V-I$ | $\sigma_V$ |
|---|---|---|
| 0.55 | 0.70 | 0.005 |
| 0.65 | 0.75 | 0.007 |
| 0.75 | 0.82 | 0.009 |
| 0.85 | 0.93 | 0.013 |
| 0.95 | 1.05 | 0.015 |
| 1.05 | 1.14 | 0.022 |
| 1.15 | 1.35 | 0.025 |
| 1.25 | 1.46 | 0.027 |
| | 1.57 | 0.030 |
| | 1.75 | 0.041 |
| | 1.88 | 0.047 |
| | 2.05 | 0.055 |
| | 2.15 | 0.068 |

**Table 4.** Listing of photometric precision as a function of main-sequence stellar colors.

of stellar brightness as well. Among the brightest sources, the variability search is sensitive to r.m.s. variations larger than $\sim$ 10 mmag. Depending upon the specific observing runs contributing data to each star's light curve, the variability search is sensitive to variations on time scales ranging from $\sim 0.3$ hours to $\sim 20$ days.

Stars with data in multiple runs were analysed on a run-by-run basis, and the results of the variability analysis for the different runs were checked for agreement. All instances in which the variability analysis gives a different result in different runs can be ascribed to differences in sensitivity between runs.

Among those stars found to be variables, we perform a Lomb-Scargle time-series analysis (Scargle (1982)) to search for the presence of a periodic signal, following the procedure described in Stassun et al. (1999). For each star a periodogram is computed at 1000 frequencies between a minimum and maximum frequency corresponding to the full time span of the light curve and one-half the typical sampling rate, respectively. We choose the highest peak in the periodogram as the best estimate for a possible periodicity in the data and estimate the statistical significance of this best period by computing a false-alarm probability (the probability that the detected period could result from random variations). The false-alarm probability is computed via a Monte Carlo simulation in which periodograms are computed for 100 purely random light curves with the same temporal sampling and photometric dispersion as the actual light curve, and the height of the highest peak in these 100 test light curves is taken to correspond to the level of 99% significance. We report a period only if its peak in the periodogram exceeds that of the 99% significance level so derived. Uncertainties in the periods are estimated as described in Paper I.

## 3. Results

### 3.1. Colour-magnitude diagrams

Though not strictly calibrated, the stellar magnitudes reported in Table 3 allow us to place most of the stars in our database on a colour-magnitude diagram. In Fig. 2 we present $V$ versus $(B-V)$ and $V$ versus $(V-I)$ colour-magnitude diagrams. The colours plotted have not been de-reddened (reddening towards M 67 is relatively small, $E(B-V) = 0.032$–$0.05$, Nissen et al. (1987), Montgomery et al. (1993)).

The cluster main sequence is clearly present amid a field of apparent non-members, extending from the cluster turnoff at $V \sim 12.5$ down to the faint limit of our database at $V \sim 18.5$[2] (the range within which our database is roughly complete). The cluster binary sequence is also clearly apparent along this full range. The stars lying below and to the blue of the cluster main sequence have been noted in studies of M 67 before and are likely due to field stars in the halo (e.g. Richer et al. (1998)). From the observing runs intended to study brighter sources (covering a few small areas in the cluster; see Table 1 and Fig. 1 in Paper I), some blue stragglers and a portion of the giant branch are also present for approximately $10 < V < 12.5$.

### 3.2. Photometric variability—General

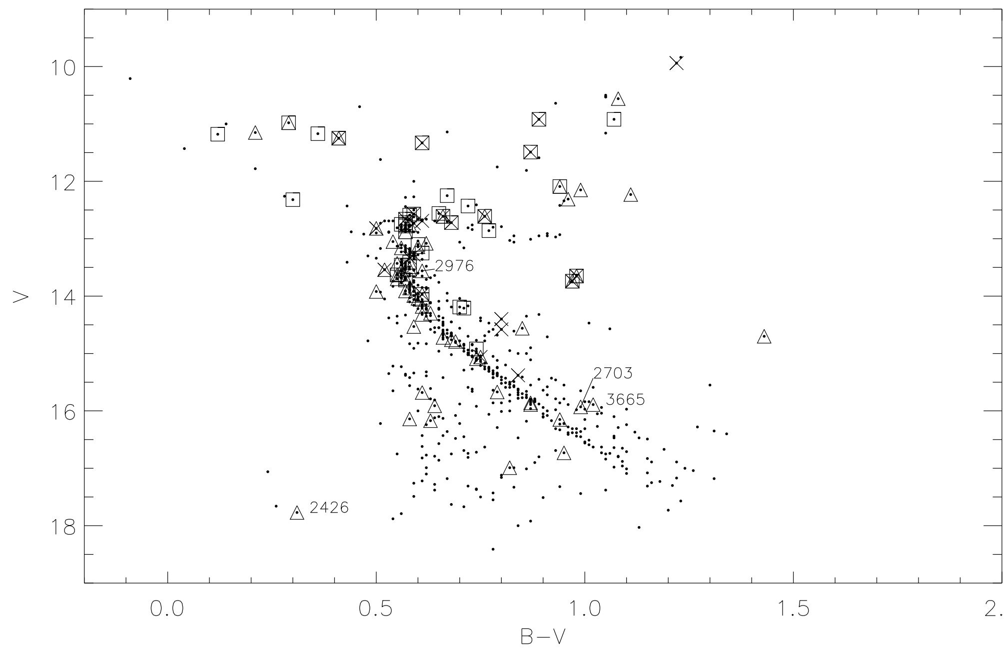
In Table 5 we present the 69 stars in our photometric database that meet the criteria for photometric variability discussed in Sect 2.3. Table 5 also provides comments for most of the stars listed. These comments give additional information such as possible periodicities, evolutionary status, binarity, etc. Stars without comments are stars situated on the cluster main sequence that display only non-periodic variability in our observations.

Our criterion for identifying a star as variable is that the probability of its light curve being constant is smaller than 0.3%. Therefore, one expects that a small number of stars ($\sim 3$) has been classified as a variable by chance. Statistically significant variability in more than one passband increases our confidence that the observed variability is real. In what follows, we refer to such stars as "high-confidence" variability candidates.

To give some clue as to the nature of the stars listed in Table 5 and, ultimately, to the physical origin of the observed photometric variability, we plot these stars in the colour-magnitude diagrams shown in Fig. 2. In addition to these variables (shown as triangles), we also indicate the known X-ray sources (shown as X's) and the known spectroscopic binaries (shown as squares). The paucity of spectroscopic binaries below $V \sim 14$ is a bias effect due to the sensitivity limit of present spectroscopic surveys in the cluster (e.g. Latham et al. (1992)). We find photometric variables in all regions of the cluster colour-magnitude diagram; we discuss stars in each of the various regions in more detail in Sect. 4.

Of the 69 variables listed in Table 5, 38 are "high-confidence" variables (i.e. they show variability in more than one passband), and of these, 29 are known proper-

[2] Note that the $B-V$ colour-magnitude diagram cuts off at $V \sim 17.5$ due to the limiting $B$ magnitude ($B \sim 18.5$) and the stellar colours at that magnitude ($B-V \sim 1$); see Fig. 2.



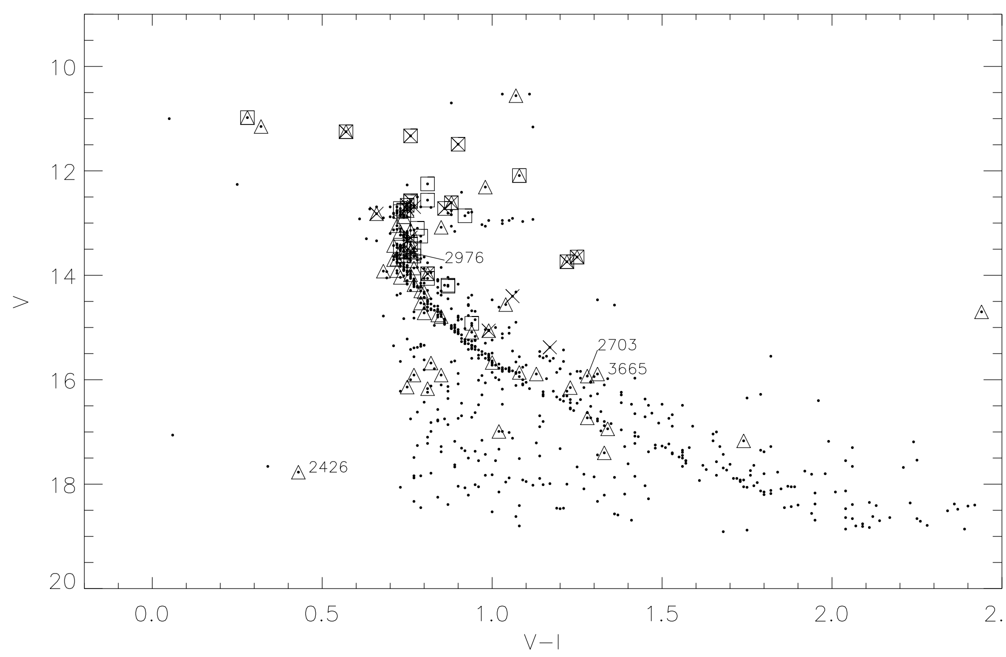




**Fig. 2.** Colour-magnitude diagrams that show $V$ versus $(B-V)$ and $V$ versus $(V-I)$ for all the stars in our observations. The variables listed in Table 5 are indicated with triangles, spectroscopic binaries with squares and X-ray sources with crosses. Periodic variables discussed in Sect. 3.3 are indicated.

motion members with a probability of 75% or greater (a total of 319 stars in our survey satisfy this membership criterion[3]; Sanders (1977); Girard et al. (1989)). Of these 29 high-confidence variable members, 16 are either known X-ray sources or binaries (or both). Another 2 stars (3780 and 4415) are situated on the binary sequence. Thus, among the proper-motion members of M 67 surveyed by us, there remain 11/319 (= 3.4%) stars (all on the cluster main sequence) that exhibit "high-confidence" variability,

[3] We note that the magnitude limits of the existing proper-motion surveys (i.e. $V \sim 16$) are much brighter than the faint limit of our survey ($V \sim 18.5$). Consequently, these variability statistics may not be representative of cluster members fainter than $V \sim 16$.

the origin of which cannot presently be associated with binarity and/or X-ray activity[4].

Similar numbers are derived from the observations of Gilliland et al. (1991). Of the 124 stars monitored by them with $V$ magnitudes within the limits of our study, 4 stars (not known to be X-ray sources or binaries) were observed to exhibit photometric variability at levels that would have been detected by us at the $3\sigma$ level or higher.

### 3.3. Photometric variability—Periodic

Aside from the X-ray sources which are the subject of Paper I, we detected definitive periods in the light curves of only four of these variable stars. These are: star 2426 ($P = 0.29$ days), star 2703 ($P = 3.7$ days), star 2976 ($P = 0.36$ days), and star 3665 ($P = 0.27$ days).

**Star 2426** is located below and to the blue of the cluster main sequence. While the best period identified by our period search (highest peak in the periodogram) is $0.1444 \pm 0.0002$ days, the data points at minimum light have sufficiently large errors that it is unclear whether or not the light curve consists of two dips with unequal depths. The $(B-V)$ and $(V-I)$ colour variations are not significant. However, additional spectroscopic and photometric observations by Orosz et al. (2001, in prep.) show this star to be an Algol-type binary (with a double-peaked light curve) with an A-star primary; the radial velocities indicate that it is not a member of M 67. In Fig. 3 the light curve for this star is shown folded on the period of 0.2888 days.

**Star 2703** is located on the cluster binary sequence and exhibits a periodic light curve with $P = 3.7 \pm 0.3$ days in $V$, and $P = 3.4 \pm 0.2$ days in $B$, both retrieved from data of run 1. The $I$ data do not show a statistically significant periodicity. The $V$-band light curve is shown in Fig. 3. The $(B-V)$ and $(V-I)$ colour variations are not significant.

**Star 2976** (S 757) is located at the top of the cluster binary sequence. The period was determined by the combined data of runs 1 and 5 ($B$ and $V$), that together cover a time span of 2 years. The best period determined by our period search is $0.18000 \pm 0.00005$ days, producing a single-peaked, roughly sinusoidal light-curve. In Fig. 3 the data are folded on the double period, as we believe this star is in fact a new W UMa system. This star was first noted to be a photometric variable by Rajamohan et al. (1988), although no periodicity was reported. The star shows no significant $(B-V)$ and $(V-I)$ colour variations. We discuss this star and our reasons for labelling it a W UMa system in Sect. 4.3.

**Star 3665** (ET Cnc, or III-79 in the nomenclature of Eggen & Sandage (1964)) is located on the cluster binary sequence and was identified as a W UMa system with a period of 6.49 hours by Gilliland et al. (1991), but no error in the period was specified. We searched for a period in a narrow window between 0.1 and 0.15 days (the power at half the period is much larger than at the full period) and find a best period from our photometry of run 1 of $0.1356 \pm 0.0004$ days (in $B$ and $V$, $0.1351 \pm 0.0004$ days in $I$) which gives a full period of $6.51 \pm 0.02$ hours, compatible with Gilliland's measurement. The data are folded on this period in Fig. 4. The system is slightly redder during primary eclipse than during secondary eclipse. This star is discussed further in Sect. 4.3.

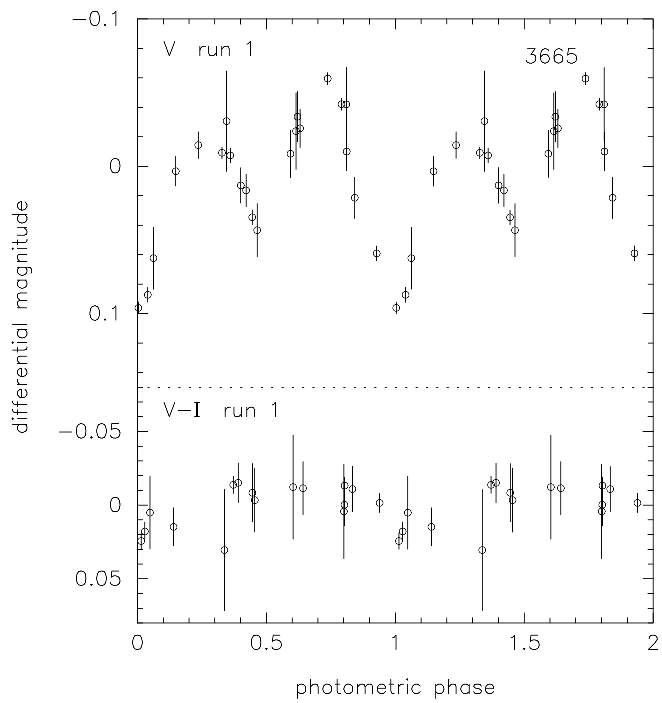



**Fig. 4.** Light and colour curves for the W UMa 3665 (ET Cnc or III-79) folded on the photometric period of 0.2712 days.

In addition to these four periodic variables, we indicate in Table 5 possible periods for another six stars (stars 2365, 3112, H, 4385, 4516, and 4712) whose light curves show some evidence for coherent variations on time scales longer than our observing windows. While our period searches did not reveal statistically significant periods for these stars, we include them here as candidate objects for follow-up study. We caution that these periods are based solely on our visual impression of the light curves, and should be taken only as a qualitative suggestion of periodicity on the timescale shown. Of course, these stars do still exhibit statistically significant variability, whether

[4] This statement is, of course, dependent on the sensitivity limits of the existing X-ray data. The ROSAT PSPC observations of Belloni et al. (1998) have a limiting $L_X \approx 8 \times 10^{29}$ erg s$^{-1}$, which is roughly a factor of $10^3$ above the X-ray luminosity of the Sun at the peak of its activity cycle (Haisch & Schmitt (1996); Acton (1996)). Thus, considerably deeper X-ray observations will be required to definitively rule out the presence of X-ray emission from these "non-X-ray sources".

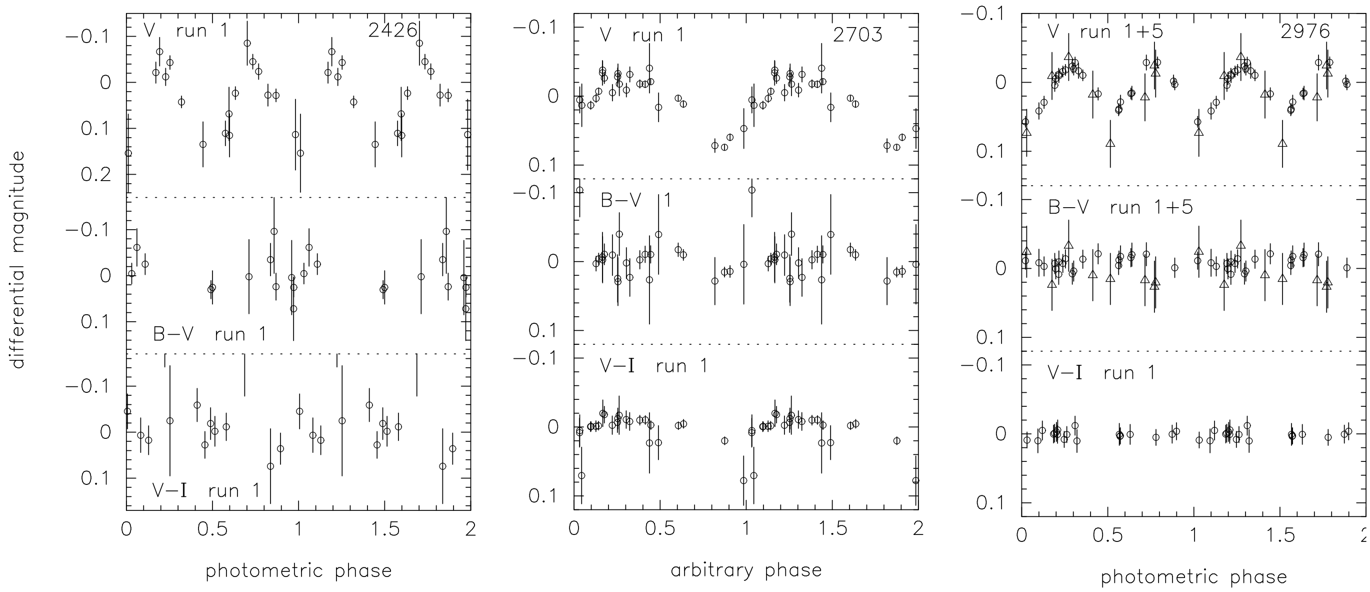



**Fig. 3.** Light and colour curves for stars 2426, 2703 and 2976 (S 757) folded on the periods of 0.2888, 3.7 and 0.3600 days, respectively (see text, Sect. 3.3). Data from different observing runs are marked with different symbols: open circles for run 1, open triangles for run 5.

or not that variability is indeed periodic. All of these stars are on the cluster main sequence.

We also list in Table 5 tentative periods for star 2280 and star C. Star 2280 is notable in that it is located far to the red of the cluster main sequence in the colour-magnitude diagram. Its colours are those of an M dwarf, so its position in the colour-magnitude diagram suggests that it is a nearby star of the M spectral type. Star C does not have the requisite colours to be placed on the colour-magnitude diagram.

## 4. Discussion

We turn now to a discussion of the nature of those stars identified as photometric variables, using the locations of these stars in the colour-magnitude diagram as a way of organising the discussion.

### *4.1. Stars below the cluster main sequence*

We have found eight variables located below the cluster main sequence. In 7 cases, our light curves show only irregular variations and, except for one star (star K), the amplitudes of the variations are small (see Table 5). The available proper-motion membership probabilities for these stars confirm non-membership in the cluster (see Tables 1 and 2). Our data provide very limited information about the nature of the observed variability. However, at the suggestion of the referee, we have closely examined the light curves for indications of RS CVn behaviour. Magnetic activity causes many RS CVn systems to be variables, due to spots on the surface of the active star(s) that rotate in and out of view. This usually results in periodic photometric variability, with amplitudes ranging from hundredths to tenths of a magnitude, typically among stars with spectral type late-F to mid-K (e.g. Strassmeier (1992)).

We do not observe periodic variability in the light curves of these stars. However, we cannot definitively exclude the possibility that these are background RS CVn systems, as spots on some RS CVn can be variable on timescales of days or even less than a single rotation period. Interestingly, we note that our light curve for star 2823 (S 845), while not strictly periodic, does show weak evidence for possible periodic behaviour (with a period of 2.9 days) for a portion of our lightcurve. Perhaps this is a field RS CVn with a rapidly evolving spot geometry. We note that our light curves for two other stars (stars 4795 and 4804) show some evidence for flaring (i.e. rapid, short-duration rises in brightness), but such flaring is evidently somewhat rare among RS CVn systems (e.g. Henry & Newsom (1996)).

While no proper-motion membership information is available for the one periodic variable below the main sequence (star 2426, see Sect. 3.3), the observations of Orosz et al. (2001, in prep.) indicate that this star is an Algol-type binary and a non-member.

### *4.2. Stars on the cluster main sequence*

In Sect. 3.3 we mentioned six stars situated on the cluster main sequence that show some evidence for periodic variability. If these tentative periods are upheld, they may be related to the stellar rotation periods (due to, e.g., starspot modulation). In addition, we have found another 21 stars on the cluster main sequence (not including the X-ray sources discussed in Paper I) whose light curves show non-periodic variations at a statistically significant level in at least one filter (Table 5). The amplitudes of

| # | S ID | Memb. | $V$ | $B-V$ | $V-I$ | $\sigma_B$ | $\chi^2_B$ | $\sigma_V$ | $\chi^2_V$ | $\sigma_I$ | $\chi^2_I$ | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2280 | | | 14.70 | 1.43 | 2.44 | *0.025* | 1.4e-02 | *0.014* | 9.1e-03 | 0.014 | 2.8e-04 | long period ($\sim$ 10 d)? nearby M dwarf? |
| 2301 | 647 | 0.99 | 13.91 | 0.57 | 0.72 | 0.017 | 2.0e-06 | 0.015 | 1.0e-07 | 0.012 | 6.2e-06 | |
| 2365 | 648 | 0.92 | 13.43 | 0.55 | 0.71 | 0.016 | 2.7e-08 | 0.019 | 1.3e-11 | 0.012 | 1.4e-07 | long period ($\sim$ 10 d)? |
| 2368 | | | 15.68 | 0.61 | 0.82 | 0.032 | 9.1e-04 | *0.026* | 8.0e-03 | 0.019 | 1.9e-05 | |
| 2414 | 828 | 0.00 | 14.53 | 0.59 | 0.79 | *0.010* | 7.9e-02 | *0.011* | 3.3e-02 | 0.009 | 2.9e-04 | |
| 2426 | | | 17.77 | 0.31 | 0.43 | *0.052* | 5.1e-02 | 0.050 | 4.8e-04 | *0.067* | 9.3e-02 | new Algol binary, $P = 0.28$ d |
| 2461 | 745 | 0.96 | 13.16 | 0.56 | 0.73 | 0.013 | 2.2e-04 | *0.007* | 3.0e-01 | *0.008* | 1.4e-01 | |
| 2526 | 844 | 0.97 | 13.70 | 0.55 | 0.71 | *0.012* | 8.2e-03 | 0.013 | 4.7e-06 | 0.012 | 7.3e-07 | |
| 2642 | | | 16.99 | 0.82 | 1.02 | 0.045 | 2.4e-03 | *0.028* | 3.7e-01 | *0.022* | 7.4e-01 | flares? below M-S, K0 colors |
| B | | | | | | | | | | 0.139 | 2.6e-12 | |
| 2646 | 843 | 0.00 | 14.72 | 0.66 | 0.80 | *0.013* | 4.7e-02 | *0.012* | 1.9e-02 | 0.013 | 9.9e-07 | |
| 2703 | | | 15.93 | 0.99 | 1.28 | 0.050 | 9.3e-05 | 0.036 | 1.6e-09 | *0.020* | 2.6e-01 | $P = 3.58$ d, on binary sequence |
| 2769 | 848 | 0.97 | 14.04 | 0.60 | 0.73 | 0.017 | 1.1e-06 | 0.014 | 1.5e-05 | 0.012 | 5.0e-08 | |
| 2823 | 845 | 0.00 | 13.92 | 0.50 | 0.68 | *0.012* | 4.1e-03 | 0.015 | 5.4e-07 | 0.011 | 1.1e-03 | below M-S, late F colors |
| 2973 | 846 | 0.90 | 13.62 | 0.56 | 0.74 | *0.011* | 1.1e-01 | 0.011 | 3.1e-05 | *0.008* | 1.8e-01 | |
| 2976 | 757 | 0.95 | 13.56 | 0.61 | 0.76 | 0.031 | 0.0e+00 | 0.029 | 0.0e+00 | 0.031 | 0.0e+00 | new W UMa, $P = 0.36$ d |
| 3034 | 1077 | 0.99 | 12.61 | 0.66 | 0.88 | 0.017 | 0.0e+00 | 0.022 | 0.0e+00 | 0.019 | 0.0e+00 | x-ray source, spect. binary, $P = 1.4$ d |
| C | | | | | | | | | | 0.142 | 0.0e+00 | $P \sim 11$ d? |
| 3111 | 2227 | 0.00 | 13.69 | 0.57 | 0.72 | 0.060 | 0.0e+00 | 0.022 | 0.0e+00 | 0.021 | 0.0e+00 | |
| 3112 | 1109 | 0.98 | 13.55 | 0.56 | 0.74 | 0.041 | 0.0e+00 | 0.021 | 0.0e+00 | 0.017 | 7.2e-12 | long period ($\sim$ 20 d)? |
| 3217 | 1063 | 0.93 | 13.65 | 0.98 | 1.25 | 0.057 | 0.0e+00 | 0.041 | 0.0e+00 | 0.029 | 0.0e+00 | x-ray source, spect. binary, $P = 22$ d? |
| 3255 | 974 | 0.00 | 15.67 | 0.79 | 1.00 | 0.080 | 0.0e+00 | 0.026 | 1.3e-12 | 0.022 | 6.7e-06 | |
| 3348 | | | 17.17 | | 1.74 | | | 0.078 | 2.5e-12 | 0.066 | 0.0e+00 | on binary sequence |
| G | | | | | | | | | | 0.082 | 2.9e-06 | |
| 3400 | 999 | 0.95 | 12.61 | 0.76 | | 0.022 | 0.0e+00 | 0.022 | 0.0e+00 | | | x-ray source, spect. binary, $P = 9.2$ d |
| 3402 | 1093 | 0.96 | 14.18 | 0.61 | 0.77 | 0.028 | 0.0e+00 | 0.023 | 0.0e+00 | *0.062* | 7.4e-01 | |
| 3439 | 1070 | 0.99 | 13.97 | 0.61 | 0.81 | 0.014 | 0.0e+00 | 0.015 | 0.0e+00 | *0.013* | 4.3e-02 | x-ray source, spect. binary, $P = 2.6$ d |
| H | | | 16.94 | | 1.34 | | | 0.242 | 0.0e+00 | 0.087 | 0.0e+00 | long period ($\sim$ 40 d)? |
| 3471 | 1082 | 0.94 | 11.25 | 0.41 | 0.57 | 0.026 | 0.0e+00 | 0.023 | 0.0e+00 | 0.025 | 0.0e+00 | x-ray source, blue straggler, binary, $P = 1.07$ d |
| 3473 | | | 15.91 | 0.64 | 0.85 | *0.014* | 6.0e-01 | 0.024 | 5.6e-05 | *0.018* | 1.0e-01 | below M-S, G2 colors |
| K | | | 15.91 | | 0.77 | | | 0.386 | 0.0e+00 | 0.195 | 0.0e+00 | below M-S |
| 3578 | 2209a[1] | 0.98 | 13.14 | 0.60 | 0.76 | 0.033 | 0.0e+00 | 0.021 | 7.4e-14 | 0.022 | 8.8e-13 | spect. binary[2] |
| 3579 | 1112 | 0.95 | 15.06 | 0.75 | 0.99 | 0.028 | 4.4e-08 | 0.022 | 1.1e-10 | *0.016* | 3.6e-02 | x-ray source, $P = 2.7$ d |
| 3586 | | | 15.89 | 0.87 | 1.13 | *0.019* | 5.2e-01 | 0.017 | 1.5e-03 | *0.012* | 6.4e-02 | |
| 3591 | 2216 | 0.99 | 15.09 | 0.74 | 0.94 | 0.044 | 3.2e-04 | *0.010* | 2.2e-01 | *0.013* | 6.2e-01 | |
| 3616 | 1113 | 0.99 | 13.74 | 0.97 | 1.22 | 0.070 | 0.0e+00 | 0.045 | 0.0e+00 | 0.047 | 0.0e+00 | x-ray source, spect. binary, $P = 2.8$ d |
| 3665 | | | 15.89 | 1.02 | 1.31 | 0.058 | 1.5e-08 | 0.056 | 1.5e-14 | 0.042 | 0.0e+00 | W UMa, $P = 0.27$ d |
| M | | | | | | | | | | 0.213 | 0.0e+00 | |
| 3706 | 1036 | 0.91 | 12.82 | 0.50 | 0.66 | 0.041 | 0.0e+00 | 0.036 | 0.0e+00 | 0.041 | 0.0e+00 | x-ray source, W UMa, $P = 0.44$ d |
| 3726 | 1279 | 0.92 | 10.56 | 1.08 | 1.07 | *0.006* | 1.0e+00 | *0.006* | 1.0e+00 | 0.014 | 6.2e-08 | giant |
| 3775 | 1264a[1] | 0.99 | 12.09 | 0.94 | 1.08 | 0.032 | 4.6e-14 | 0.025 | 5.6e-06 | *0.014* | 1.4e-01 | spect. binary, giant |
| 3780 | 1264b[1] | 0.79 | 13.08 | 0.62 | 0.85 | 0.054 | 0.0e+00 | 0.057 | 0.0e+00 | 0.058 | 0.0e+00 | on binary sequence |
| 3789 | 1341 | 0.94 | 14.79 | 0.69 | 0.85 | *0.011* | 1.6e-01 | *0.011* | 5.5e-03 | 0.009 | 1.8e-03 | |
| 3858 | 1263 | 0.89 | 11.15 | 0.21 | 0.32 | 0.016 | 1.9e-06 | 0.027 | 0.0e+00 | 0.015 | 2.8e-03 | blue straggler |
| 3905 | 1284 | 0.95 | 10.98 | 0.29 | 0.28 | *0.009* | 8.0e-01 | *0.007* | 9.9e-01 | 0.013 | 3.6e-11 | blue straggler, spect. binary |
| 3949 | 1305 | 0.95 | 12.31 | 0.96 | 0.98 | *0.016* | 6.1e-01 | *0.012* | 9.5e-01 | 0.021 | 1.1e-09 | giant |
| 3994 | 1282 | 0.95 | 13.54 | 0.52 | 0.76 | 0.131 | 0.0e+00 | 0.135 | 0.0e+00 | 0.130 | 0.0e+00 | x-ray source, W UMa, $P = 0.36$ d |
| 4006 | | | 17.40 | | 1.33 | | | 0.080 | 4.8e-08 | *0.050* | 1.5e-02 | below M-S |
| 4008 | 1344 | 0.96 | 13.86 | 0.58 | 0.77 | 0.014 | 4.2e-06 | 0.013 | 1.5e-06 | *0.008* | 3.6e-02 | |
| 4039 | 1293 | 0.93 | 12.15 | 0.99 | | *0.006* | 9.7e-01 | 0.020 | 6.0e-10 | | | giant |
| 4050 | | | 15.86 | 0.87 | 1.08 | *0.019* | 1.8e-01 | *0.022* | 9.4e-03 | 0.015 | 2.7e-03 | |
| 4337 | 1224b[1] | 0.64 | 13.63 | 0.55 | 0.77 | 0.096 | 0.0e+00 | 0.035 | 0.0e+00 | 0.042 | 0.0e+00 | spect. binary, rad. vel. member[2] |
| 4341 | 1224a[1] | 0.86 | 13.41 | 0.58 | 0.76 | 0.053 | 0.0e+00 | 0.014 | 4.4e-04 | 0.020 | 3.9e-15 | spect. binary[2] |
| 4385 | 1507 | 0.95 | 13.53 | 0.58 | 0.73 | 0.015 | 6.3e-09 | 0.014 | 6.7e-09 | 0.010 | 4.0e-04 | long period ($\sim$ 20 d)? |
| 4415 | 1506 | 0.93 | 12.76 | 0.58 | 0.75 | 0.013 | 1.4e-05 | 0.014 | 1.8e-05 | *0.011* | 1.6e-02 | on binary sequence |
| 4429 | 1504 | 0.91 | 13.99 | 0.59 | 0.76 | *0.012* | 6.1e-03 | 0.011 | 1.7e-03 | 0.011 | 2.0e-04 | |
| 4491 | | | 16.15 | 0.94 | 1.23 | *0.032* | 1.5e-01 | 0.025 | 6.0e-06 | *0.016* | 9.4e-01 | |
| 4516 | 1497 | 0.00 | 14.32 | 0.61 | 0.80 | *0.010* | 2.4e-01 | 0.012 | 7.4e-07 | *0.007* | 3.4e-01 | long period ($\sim$ 10 d)? |
| 4555 | | | | | | | | | | 0.042 | 3.1e-09 | |
| 4619 | 1508 | 0.99 | 12.88 | 0.57 | 0.74 | 0.022 | 0.0e+00 | 0.018 | 6.0e-15 | 0.014 | 3.6e-05 | spect. binary, M-S turnoff |
| 4654 | 1492 | 0.01 | 14.56 | 0.85 | 1.04 | *0.011* | 8.8e-01 | *0.007* | 5.4e-01 | 0.010 | 1.0e-03 | on binary sequence |
| 4656 | 1505 | 0.79 | 14.30 | 0.63 | 0.79 | 0.017 | 2.1e-09 | 0.017 | 3.3e-13 | 0.013 | 4.2e-11 | |
| 4679 | 1509 | 0.00 | | | | 0.021 | 3.1e-04 | | | | | |
| 4705 | 1503 | 0.93 | 13.05 | 0.54 | 0.72 | 0.015 | 2.6e-05 | 0.014 | 4.4e-07 | 0.013 | 2.3e-05 | |
| 4712 | | | 16.73 | 0.95 | 1.28 | 0.143 | 1.0e-13 | *0.024* | 8.0e-02 | *0.018* | 4.4e-01 | long period ($\sim$ 20 d)? |
| 4795 | | | 16.17 | 0.63 | 0.81 | 0.027 | 2.0e-03 | *0.019* | 4.9e-03 | *0.020* | 1.1e-01 | below M-S, G2 colors |
| 4804 | | | 16.14 | 0.58 | 0.75 | *0.022* | 2.1e-01 | 0.023 | 1.1e-03 | *0.018* | 7.9e-02 | below M-S, G0 colors |
| 4820 | 2211 | 0.92 | 14.76 | 0.68 | 0.84 | 0.042 | 1.4e-03 | *0.007* | 5.0e-01 | *0.009* | 1.5e-01 | |
| 4859 | | | 12.23 | 1.11 | | 0.023 | 1.7e-11 | 0.022 | 1.1e-16 | | | repeating dips? giant? |

[1]Photometry possibly contaminated by close neighbor.
[2]Source: R. Mathieu, unpublished data

**Table 5.** List of variable stars. From left to right: identification number from Table 1 and Table 2; identification number and proper-motion membership probability from Sanders (1977) or Girard (1989) if available; average $V$ magnitude and $B-V$ and $V-I$ colours from our photometry as listed in Table 3; r.m.s. of the light curves in $B$, $V$ and $I$, and corresponding $\chi^2$ probabilities, r.m.s. values in *italics* are not significant at the $3\sigma$-level; comments.

variability exhibited by a few of these stars is remarkably large (few tenths of a mag; see Fig. 1). Our data do not shed much light on the nature of this variability. Perhaps the variations we observe have their origin in magnetic activity on the surfaces of these G and K stars.

Fifteen of these 27 stars are high-confidence variables, showing statistically significant variability in more than one filter. Of these, 11 are known proper-motion members of the cluster (see Sect. 3.2). As discussed in Sect. 3.2, photometric variability at the levels to which our survey is sensitive ($\sim$ 1–2%) is evidently rare among the main-sequence members of M 67, with an occurrence rate of at most a few percent in those observed by us.

### 4.3. Stars on the cluster binary sequence

Photometric variables on the cluster binary sequence are interesting because such variability can point the way to the discovery of interacting binary systems. If periodic, the observed variability may be related to the dynamics

of the binary system. Three of the variables for which we found a photometric period are situated on the cluster binary sequence.

The two most notable variable stars on the cluster binary sequence in our observations are the two W UMa (contact binary) systems, stars 3665 and 2976, which have already been introduced in Sect. 3. The former (ET Cnc) was discovered by Gilliland et al. (1991) while the latter is newly discovered here. ET Cnc has a primary-eclipse depth in $V$ of 0.16 mag, and a secondary-eclipse depth of 0.1 mag. The unequal eclipses in the observed light curve potentially indicate that the system is in poor thermal contact or is semi-detached (see also discussion in Paper I on the X-ray source W UMa S 1036).

We have discovered that star 2976 (S 757) is a strong candidate for being a W UMa system in M 67. Sanders (1977) gives this star a proper-motion membership probability of 95%. The most likely period from our time-series analysis is 0.1800 days, which we interpret as the half-period of 0.3600 days, assuming two eclipses of very similar depth. Spectroscopic radial-velocity measurements will be needed to confirm this period. Nonetheless, a period of 0.36 days places this star on the W UMa period-colour relation (e.g. Rucinski (1993)) very well, given its $(B-V)$ colour of 0.61. We note that Sandquist & Shetrone (2001) have also recently reported detection of eclipses in this star with a period of $P \sim 0.4$ days.

The discovery of this new W UMa variable brings the total number of such contact binaries in M 67 to four. We can estimate the frequency of W UMa systems in M 67 by comparing this number to the number of proper-motion cluster members from, e.g., the study of Girard et al. (1989). The Girard et al. study includes 367 proper-motion members (probability $\geq 75\%$) among stars with $V < 15.5$ in a region $34' \times 42'$ about the cluster centre. This yields a W UMa frequency of $4/367 = 1.1\%$, which is consistent with the contact-binary frequency in other Galactic open clusters of $\sim 1\%$ (Rucinski (1998)). We note that while the new W UMa discovered by us is contained in the Girard et al. study, one of the three previously known systems is not (ET Cnc is a bit too faint with $V = 15.8$), even though it is within the spatial boundaries of that study. And the spatial area of the present study is somewhat smaller than that of the Girard et al. study. As noted by Rucinski (1998), a detailed accounting of contact-binary statistics is made difficult because of these differences in depth and spatial coverage of different studies. Even so, the W UMa frequency in M 67 is evidently of order 1%.

In addition to these two contact binary systems, we have also discovered periodic variability in another star on the cluster binary sequence, star 2703 with a period of 3.6 days. While our data permit us to say little about this star, its location in the colour-magnitude diagram and its periodic light curve make this a prime candidate for follow-up spectroscopic monitoring. Perhaps the observed photometric period corresponds to the binary orbital period. No membership information is presently available for this star.

Four stars (3348, 3780, 4415, 4654) situated on the cluster binary sequence did not evince periodic variability in our data, but nonetheless showed statistically significant variability. Star 4415 (S 1506) is a proper-motion member and was monitored by Mathieu et al. (1986) for radial-velocity variations, but no indication of binarity was found ($\sigma = 1$ km s$^{-1}$ in 8 observations spanning 2 years); perhaps this is a wide binary. Star 4654 (S 1492) is a proper-motion non-member, and in any case its photometric variability is only significant in one filter. The other 2 stars, both of which are "high-confidence" variables, deserve spectroscopic follow-up to determine if they are interacting binary systems. Star 3780 (S 1264b) is a proper-motion member, but we note that its photometry might be affected by the presence of a close neighbor. Star 3348 does not presently possess cluster membership information.

Finally, we have found four stars (3578, 4337, 4341, 4619) showing statistically significant variability that are also known spectroscopic binaries (R. Mathieu, private communication). Star 4337 (S 1224b) has an orbital period of 12.44 days and an eccentricity of 0.03. Star 4341 (S 1224a) has an orbital period of 726 days, and an eccentricity of 0.3. For star 3578 (S 2209a) no orbital solution has yet been derived. The light curves of these three stars show no evidence for periodicity on the orbital or pseudo-synchronous periods (Hut 1981). However, we caution that our photometry for these stars may be contaminated by close neighbors. Star 4619 (S 1508), situated at the cluster turnoff, was found by Mathieu et al. (1990) to be a spectroscopic binary with an orbital period of 25.9 days and an eccentricity of 0.44. The $BVI$ light curves of this star do not show evidence for periodic variability on the spectroscopic orbital period or the pseudo-synchronous period of 11.2 days. This star's $V$-band light curve is shown in Fig. 5.

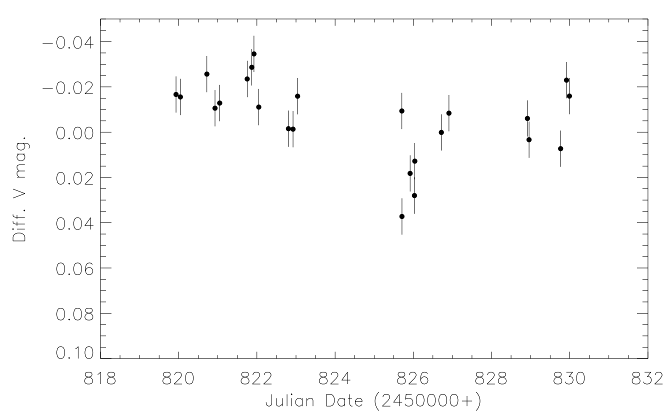



**Fig. 5.** $V$-band light curve for the spectroscopic binary, star 4619 (S 1508).

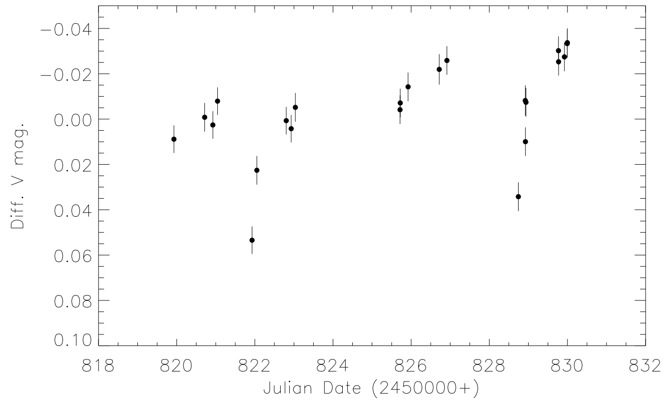



**Fig. 6.** $V$-band light curve for the giant star 4859.

### 4.4. Giant stars

Five of the variables reside on the red giant branch of the cluster colour-magnitude diagram. These variables show relatively low levels of variability, with r.m.s. $\sim 0.02$ mag. We note that for three of these five stars, the observed variability is statistically significant in only one of the filters observed (i.e. they are not "high-confidence" variables). For the other giant stars included in our observations, we can place $3\sigma$ upper limits on variability of $\sim 0.015$ mag, based on the limiting photometric precision of our photometry for the brightest sources.

Star 3775 (S 1264a) is a spectroscopic binary, and should be monitored further to study any possible connection between the binary orbit and photometric variability. While a "high-confidence" variable, we caution that our photometry is suspect due to the presence of a close neighbor. Mathieu et al. (1986) monitored the giants 3726 (S 1279), 4039 (S 1293), and 3949 (S 1305), but found no evidence for radial-velocity variations ($\sigma \leq 0.5$ km s$^{-1}$ in about 15 observations spanning more than 10 years, for all three stars). Thus we consider it unlikely that the variability, if real, is related to binarity. Henry et al. (2000) found a large fraction of low-amplitude ($\sim 0.01$ mag) photometric variables among a sample of 187 G ($\sim 25\%$) and K ($\sim 50\%$) giants. For the group of giants of type earlier than K2—which includes our four variable giants—they exclude both radial pulsation and rotational spot-modulation as the origin of the brightness variations. Henry et al. suggest that non-radial, $g$-mode pulsations most likely give rise to the variability.

Interestingly, star 4859, the other high-confidence variable on the giant branch, shows a peculiar light curve, with rapid, short-duration dips (Fig. 6). Unfortunately, being situated in the far outskirts of the cluster, no membership information is available for this star.

### 4.5. Blue stragglers

Two of the blue stragglers in M 67 not detected in X-rays show statistically significant photometric variability in our data. Photometric variability among blue stragglers is particularly interesting in light of the uncertain evolutionary status of these objects. Photometric variability may be a clue to the presence of a binary companion (e.g. in the case of the eclipsing blue straggler S 1082, see Goranskij et al. (1992); van den Berg et al. (2001a)) or may provide information on the stellar structure of the stars (in the case of oscillations, see discussion in Gilliland & Brown 1992).

Star 3905 (EX Cnc or S 1284) is a spectroscopic binary that shows low-amplitude photometric variations with a period of $\sim$ 1.3 hours first discovered by Gilliland et al. (1991), Gilliland & Brown (1992), and Simoda (1991). The $B$ and $V$ light curves we obtained during the highly sampled run 4 show a similar behaviour. These short-timescale variations are probably related to the star's position within the $\delta$ Scuti instability strip and not to the orbital period of 4.2 days (Milone & Latham (1992a)).

Star 3858 (S 1263) was monitored spectroscopically by Milone & Latham (1992b), but no orbit was determined. Gilliland et al. included this star in their search for solar-analog oscillations, but observed an r.m.s. scatter of only 0.005 mag. Simoda (1991) similarly found no evidence for photometric variability, but Kim et al. (1996) do report a high dispersion in the light curve of this star. The light curves that result from our observations also display a large scatter (up to 0.03 mag), and this variability is statistically significant in all three bands. While our results and those of Simoda and Kim et al. can be explained in terms of sensitivity differences of the studies, the Gilliland et al. result suggests that the variability observed by us and by Kim et al. does not persist at all times.

## 5. Conclusions

Our survey of photometric variability among 990 stars in the old open cluster M 67 detected 69 variable stars. Among the brightest sources in our sample, detection of variability $\sigma \approx 10$ mmag (with $> 3\sigma$ confidence) is achieved; for the typical star observed, sensitivity to variability at levels $\sigma \approx 20$ mmag is achieved. Membership information is available for 439 stars (46 variables) included in our observations and marks 319 (38 variables) as members with a probability of at least 75% (Sanders (1977); Girard et al. (1989)). Of these 38 variable cluster members, 29 exhibit variability in more than one of the passbands used, increasing our confidence that the observed variability is real. Nine of these stars are periodic variables.

In all cases the amplitude of variability is low, ranging from a few hundredths to a few tenths of a magnitude. Our study is sensitive to brightness variations on time scales of 0.3 hours to $\sim$ 20 days. Apparently, at the age of M 67 variability on these time scales and at these amplitudes is strongly associated with binarity, as 14 of the 29 "high-confidence" variable members are known binaries. One of the other high-confidence variables (S 1112) is an X-ray source for which binarity has not been established,

another is a blue straggler (S 1263), and still two others are situated on the cluster binary sequence. *Periodic* variability is especially rare for single stars, for in 8 of the 9 periodic variable members observed by us (including the new candidate contact system S 757), 7 of which are X-ray sources, the variability finds its origin in the binary nature of the stars (eclipses, ellipsoidal variations, rotational spot-modulation in tidally locked binaries). This confirms the picture that rapid rotation in an old population can only be maintained in close binaries.

In the contact binary 3665 (ET Cnc), for which no membership information exists, the variability is the result of binarity as well. We encourage spectroscopic observations of the three remaining stars that exhibit periodic variations (the faint and blue star 2426 and star 2703 on the binary sequence, both without membership information) and the member 3579 (S 1112, discussed in paper I) to establish their binary status and/or obtain an indication for membership from their radial velocity.

Also, more observations should be obtained of the stars for which we provide tentative periods, in the first place to further examine if their photometric variability is indeed periodic and secondly to establish if they are single or binary.

The origin of the photometric variability for the remaining stars discussed in this paper is in most cases unknown. As possible causes for the variations we suggest low-level surface activity, stellar pulsations or, especially for the stars on the binary sequence, binary interaction.

*Acknowledgements.* The authors wish to thank Magiel Janson, Rien Dijkstra, Gertie Geertsema, Remon Cornelisse and Gijs Nelemans for obtaining part of the data used in the paper. The Kitt Peak National Observatory is part of the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation. The Jacobus Kapteyn Telescope is operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias. The Dutch 0.91-m Telescope was operated at La Silla by the European Southern Observatory. Support for this work was provided by NASA through Hubble Fellowship grant HST-HF-01144.01-A by the Space Telescope Science Institute, which is operated by AURA, for NASA, under contract NAS 5-26555. This research made extensive use of the WEBDA Open Cluster Database developed and maintained by J.-C. Mermilliod. MvdB is supported by the Netherlands Organization for Scientific Research (NWO).

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